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Research Article

Evaluating brown trout as a potential biological control agent of signal crayfish

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Abstract

This study evaluates the potential of brown trout (*Salmo trutta*) as a biological control of a recently established signal crayfish (*Pacifastacus leniusculus*) population in a protected area (Baceiro River, Montesinho Natural Park, Portugal). Five sampling sites were monitored throughout 2023. Results indicated that brown trout were able to predate on signal crayfish but did so infrequently as only 12.24% of the sampled fish showed signs of signal crayfish in their stomachs. The number of signal crayfish in the stomach contents of brown trout was also low (only 2.13% of all prey items), but accounted for 17.70% of the total biomass of all retrieved prey items. Predation was higher in the warmer months and was size-dependent, with larger fish more able to predate on this non-native crayfish species. These findings highlight that, although brown trout can prey on signal crayfish, their effectiveness as a biological control agent is limited due to their lower abundance and predation rates. However, this situation may change in the future since brown trout may increasingly consume signal crayfish as they become more familiar with this novel prey. Therefore, it is important to conserve key native populations, and even reinforce their abundance, to allow communities to develop effective resistance to non-native species. In the meantime, a multifaceted management approach that incorporates additional control strategies, such as mechanical removal, is recommended to reduce the abundance and biomass of signal crayfish, potentially mitigating their impact and helping to maintain ecosystem balance in this protected area.

Key words: Biocontrol, freshwater ecosystems, Montesinho Natural Park, non-native species, *Pacifastacus leniusculus*, *Salmo trutta*

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Introduction

Non-native species are a major threat to biodiversity, particularly in freshwater ecosystems (Strayer 2010; Gallardo et al. 2016). Among these, the signal crayfish (*Pacifastacus leniusculus*) stands out as one of the most ecologically disruptive non-native species in Europe (Krieg et al. 2020). Native to North America, this species was introduced primarily for aquaculture and commercial reasons (Holdich et al. 2014), but has rapidly expanded its range, interacting with native species for resources and habitat use and altering key ecological processes (Galib et al. 2021; Alves et al. 2025). Its presence leads to cascading effects on freshwater ecosystems, including changes in trophic interactions, reductions in native biodiversity,

and habitat degradation (Carvalho et al. 2022a, 2025). The first documented occurrence of signal crayfish in Portugal dates back to 1997 in the Maçãs River (Bernardo et al. 2011), and since then, this non-native species has been increasing in abundance and expanding its distribution in the northeast part of the country (Anastácio et al. 2019; Meira et al. 2019; Carvalho et al. 2025).

Traditional control measures applied to signal crayfish, such as mechanical removal and chemical treatments, often fail to provide long-term solutions and can have unintended ecological consequences (Moorhouse et al. 2014; Peay et al. 2019). A promising alternative is the use of native predators such as eels (*Anguilla anguilla*) to regulate non-native crayfish populations, leveraging natural ecological interactions to restore balance within affected ecosystems (Aquiloni et al. 2010; Musseau et al. 2015). Given the ecological impact of signal crayfish and the challenges of traditional control methods in mountainous oligotrophic rivers, investigating the role of potential native predators, such as brown trout (*Salmo trutta*), is crucial to understanding whether this fish can contribute as a biological control of this non-native species. The brown trout, a widely distributed species in European freshwater ecosystems, is known for its opportunistic feeding behavior, including crayfish species (Bridcut and Giller 1995). As a visual predator, brown trout primarily rely on sight to capture prey, with feeding activity peaking at dawn and dusk (Klemetsen et al. 2003). This behavioral pattern aligns with the described nocturnal activity of signal crayfish (Sbragaglia and Breithaupt 2022), making this non-native species potentially vulnerable to predation during crepuscular hours. Additionally, larger brown trout have been observed to incorporate progressively larger prey into their diet, suggesting that adult individuals could exert significant predation pressure on crayfish populations (Klemetsen et al. 2003).

Although predation by brown trout may contribute to the control of signal crayfish, its effectiveness depends on various ecological factors, including prey availability, environmental conditions, and the adaptability of both species (Carlsson et al. 2009). Moreover, there may be a lag period before native predators recognize non-native crayfish as a viable food source, potentially allowing their populations to expand before significant predation pressure is exerted (Carroll 2007; Cox 2013). In fact, several studies report increased consumption (and even regulation) on non-native populations with increasing invasion time (Siemann et al. 2006; Carlsson and Strayer 2009; Carlsson et al. 2011; Santamaría et al. 2022), others indicate no such change (Carpenter and Cappuccino 2005; Pintor and Byers 2015). Given this background, and because prevention (signal crayfish is already in the system) and eradication (signal crayfish is already widespread in the studied protected area) are no longer viable solutions, understanding the potential role of brown trout as a natural predator is essential for assessing the viability of biological control as a sustainable management strategy (e.g. better conserve or even re-stock brown trout populations in invaded areas). Therefore, this study aimed to: i) assess the degree of predation of brown trout on the signal crayfish; ii) assess possible spatial and temporal differences in predation rates; and iii) evaluate if this predation is size-dependent. We hypothesise that: i) brown trout will predate on signal crayfish, with predation rates being higher in sites where crayfish are more abundant; ii) predation rates will increase in warmer months due to greater activity of both species; and iii) larger trout will consume more crayfish.

Material and methods

Study area

Our study area comprised five sampling sites along the Baceiro River (Fig. 1), within the Montesinho Natural Park (NE Portugal), a protected area created in 1979 (Castro et al. 2010). This protected area has a high biodiversity, hosting, for example, about 80% of Portugal's mammal species. The Baceiro River, with a total length of 60 km, originates in Spain and belongs to the Douro basin (Sousa et al. 2019). The area has very low human disturbance and harbors a rich aquatic biodiversity with high conservation status (e.g. Pyrenean desman *Galemys pyrenaicus*, classified as Endangered by the IUCN Red list). Regarding the fish community, only native species are present in the studied area and comprised the brown trout (*Salmo trutta*) classified as Least Concern by the IUCN Red list, the Northern straight-mouth nase (*Pseudochondrostoma duriense*) classified as Near Threatened, the Iberian barbel (*Luciobarbus bocagei*) classified as Near Threatened, and the Northern Iberian chub (*Squalius carolitertii*) classified as Near Threatened (Oliveira et al. 2025). The five sampling sites have a similar width (around 6 m) and the altitude varies between 594 m in the most downstream site (B1) and 835 m in the most upstream site (B5). This river is an ideal area for studying predator-prey interactions given the lack of other (besides biological invasions) significant human disturbances, such as pollution and the presence of dams (Sousa et al. 2019, 2020). The signal crayfish was first detected in the Baceiro River in 2013 (Sousa et al. 2015).

Environmental characterization

The following environmental parameters were measured using a HACH HQ2200 multi-parameter probe at every sampling site and throughout the study period: pH, total dissolved solids (mg/L), conductivity (µS/cm), dissolved oxygen (mg/L), and temperature (°C). This environmental characterization was consistently performed in all five sampling sites across nine different time periods (from April to December) throughout the entire year of 2023.

Brown trout and signal crayfish data collection

Brown trout feed, preferably, in the early hours of the day, so their collection was carried always in the morning to coincide with their natural feeding behavior. Fish were captured using electrofishing (Hans Grassl™ ELT60II-GI; 300–600 V, DC, 2200W) for a period of 30-minutes at each sampling site along a standard length of 150 meters of the river channel, comprising an area of about 1000 m^2 in each site. To guarantee site independence between locations, and to reduce the possibility of *S. trutta* moving between sampling sites, locations were separated by at least 1 km. This allows for site independence, since resident brown trout *S. trutta* shows high site fidelity, normally staying within a few hundred meters of their preferred spots for much of the year (Ovidio et al. 2002; Höjesjö et al. 2015). The relative abundance of brown trout per site was expressed as the total number of individuals per catch per unit of effort (ind. CPUE). We prefer to use the term abundance rather than density, as the sampling procedure may introduce some bias and is unlikely to capture all the trout within the 1000 m^2

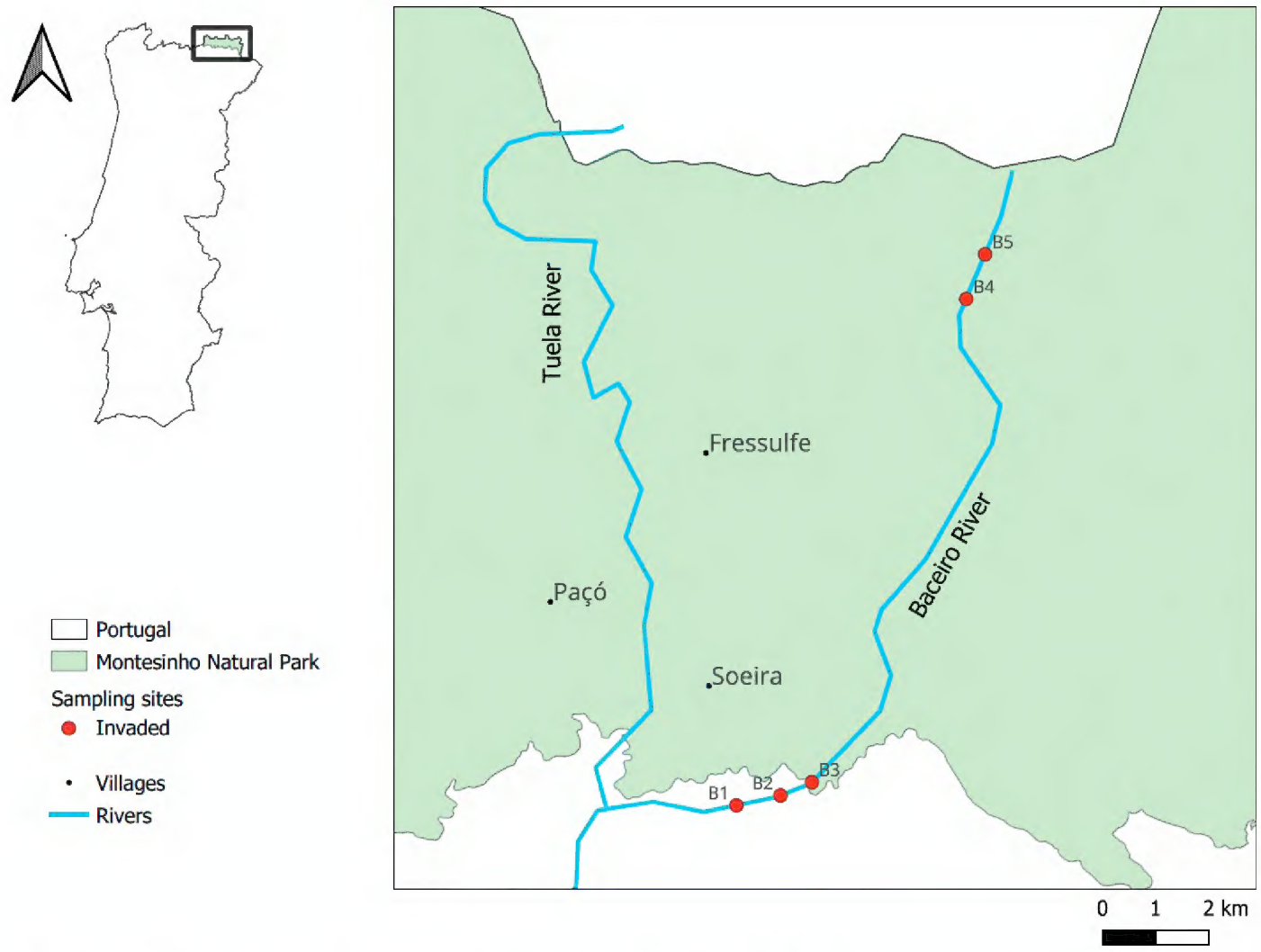

Figure 1. Map of the surveyed area showing the location of the 5 sampling sites in Baceiro River. Map was produced using QGIS software (QGIS Development Team, 2022).

area surveyed. Nevertheless, since the sampling was consistently conducted by the same experienced operators, we are confident that comparisons between sampling sites and across different times of the year remain valid.

A total of 8 to 10 traps were used per site to capture signal crayfish, and left underwater for 24 hours. These traps were specifically used for decapod crustaceans, reducing the chances of possible bycatch of other species, namely fish. Traps were all cylindrical (43 cm *d*, 22 cm *h*; 1.5 cm mesh) and were baited with dead marine fish (*Trachurus trachurus*). These traps were strategically placed in areas such as pools, riffles, areas near the banks, and the central part of the river channel. The relative abundance of signal crayfish per site was expressed as the total number of individuals per catch per unit of effort (ind. CPUE).

This biotic characterization was consistently performed at all five sampling sites across nine different time periods (from April to December) throughout the entire year of 2023. It should be noted that from January to March, and due to the high precipitation and high river flow, it was impossible to perform electrofishing and to place the traps to characterize the brown trout and signal crayfish populations, respectively.

Brown trout diet

A total of 825 stomach contents of brown trout were analyzed to determine whether the signal crayfish was present in their diet. This was done through a simple, non-lethal technique, which involved squirting water into the stomach to induce regurgitation (following Sánchez-Hernández et al. 2010). Once the samples were collected, trout were carefully returned to the river to minimize stress and mortality. Individuals present in the stomach content were identified using Tachet et al. (2010) and were counted. Then, individuals identified for each taxon were dried at 60 °C for 48 h to record their biomass (dry weight).

Data analysis

A Principal Component Analysis (PCA) was conducted to assess how abiotic factors, including temperature, oxygen, conductivity, total dissolved solids (TDS), and pH, vary across the five sampling sites over time. The variables were normalized and analyzed enabling the categorization of sites based on their environmental characteristics.

To assess the spatial and temporal changes in brown trout and signal crayfish relative abundances, a two-way ANOVA was performed to assess the effects of Site and Julian Day (JD) and their interaction. Post hoc pairwise comparisons were conducted using Tukey's Honest Significant Difference (HSD) test based on estimated marginal means (EMMs) for Site, JD, and their interaction to explore differences between groups.

To assess whether abiotic and biotic factors influenced crayfish predation by brown trout, we used a Generalized Linear Model (GLM) with a binomial distribution and logit link function. The response variable was crayfish presence in brown trout stomach contents (0 = absent, 1 = present), and predictor variables included brown trout length (cm), water temperature (°C), total dissolved solids (TDS, mg/L), pH, crayfish relative abundance (ind. CPUE/24h), sampling site (categorical), and JD (categorical). We tested for multicollinearity among predictor variables using the Variance Inflation Factor (VIF), considering values > 5 as indicative of multicollinearity issues. Due to a strong negative correlation between temperature and dissolved oxygen (r = -0.89), we excluded dissolved oxygen from the final model to avoid redundancy. Similarly, total dissolved solids (TDS) showed a very high correlation with conductivity (r = 0.99) and so conductivity was also removed to prevent collinearity issues. Model diagnostics were performed by examining residual plots to ensure the appropriateness of the GLM. All analyses were conducted in R using the glm() function from the base stats package.

All statistical analyses were carried out using the R Studio software (R Core Team, 2021).

Results

Environmental characterization

The results of the abiotic characterization per site and over time can be seen in Suppl. material 1: table S1. The PCA categorized the sampling sites into two major groups (Fig. 2). The first group, which includes sites B1, B2, and B3, was characterized by higher conductivity and TDS values, while the second group, with sites B4 and B5, showed lower values for these variables. PC1 explains 68.59% of the total variance, with the primary contributions coming from conductivity and TDS (negative side). PC2 accounted for 18.68% of the total variance and was strongly influenced by temperature. Dissolved oxygen and pH had minimal influence.

Brown trout and signal crayfish population dynamics

Brown trout abundance varied across space and time. Sites B4 and B5 showed a sharp increase, peaking around JD 226, followed by a decline (Fig. 3). In contrast, sites B1, B2 and B3 exhibited more gradual increases with generally lower abundance (Fig. 3). ANOVA indicated a marginal effect of sampling sites on trout

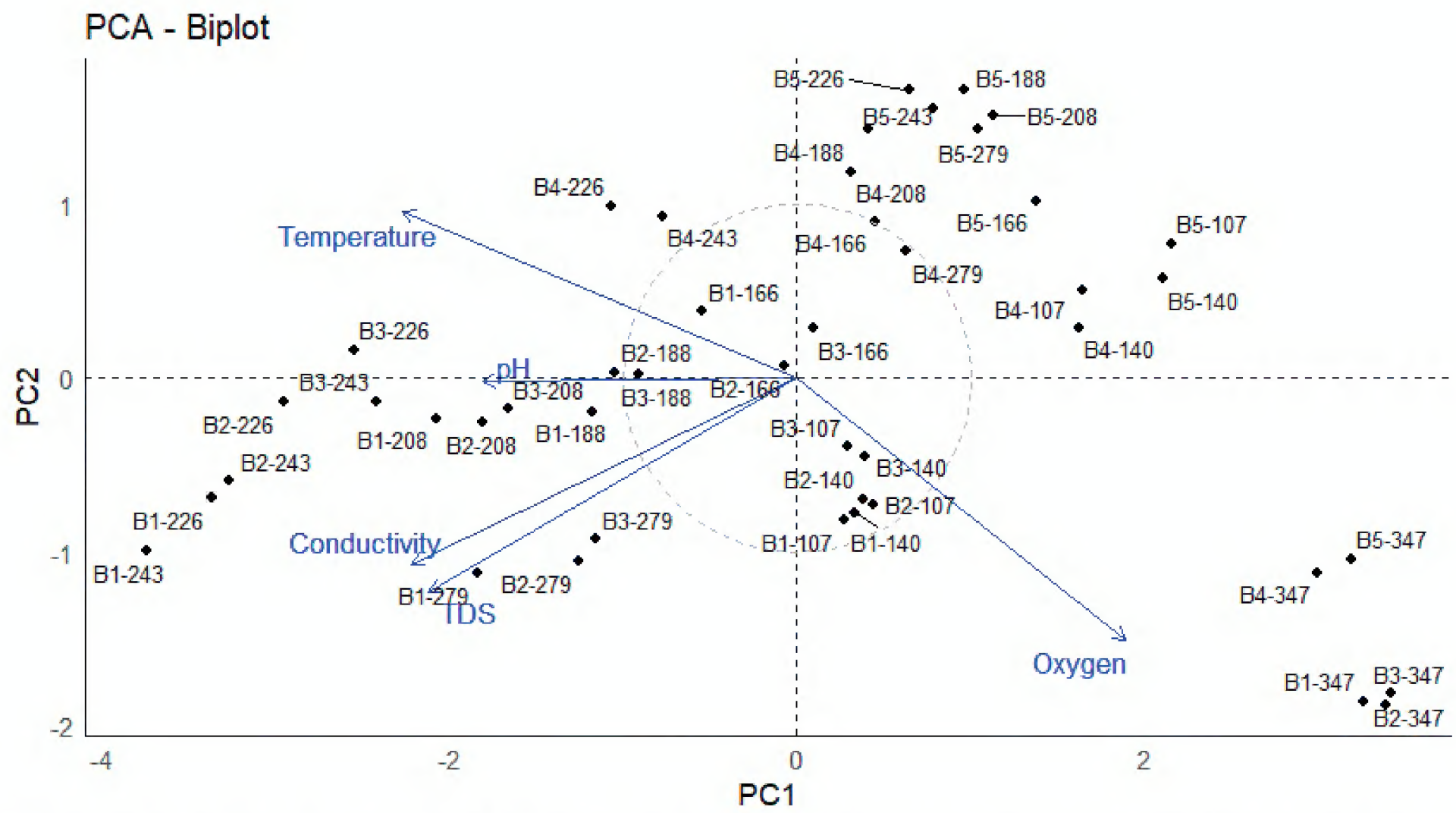

Figure 2. Principal Components Analysis (PCA) showing the arrangement of the five sampling sites based on the abiotic factors measured throughout the year. PC1 explains 68.59% of all variance and PC2 18.68%.

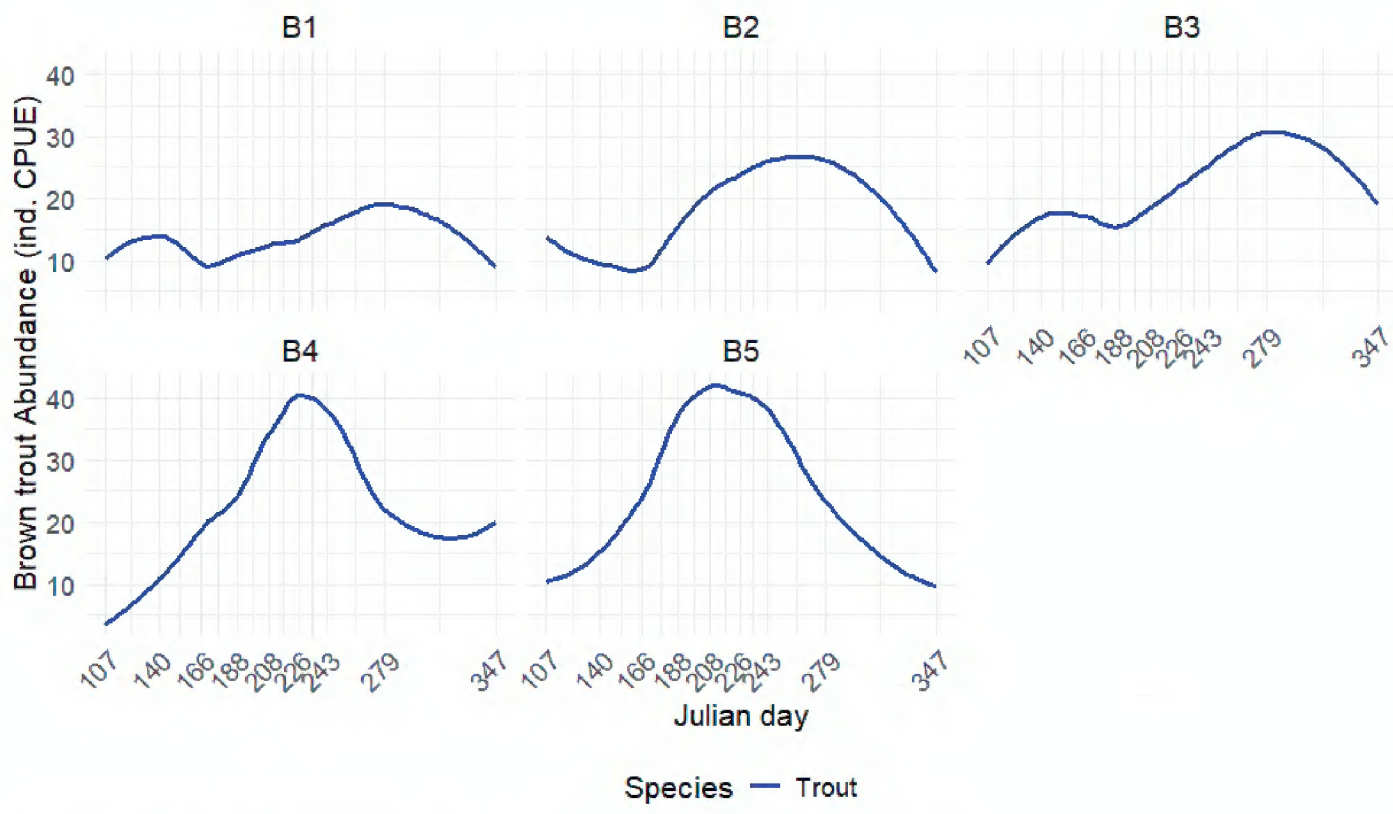

Figure 3. Abundance of brown trout over time and sampling sites.

abundance (p = 0.0566), with post-hoc comparisons revealing that site B5 had significantly higher abundance than site B1 (p = 0.046), while differences among other sites were not statistically significant. ANOVA confirmed a significant effect of JD on brown trout abundance ($F_{(8, 45)}$=4.86, p < 0.001), with Tukey's test revealing higher abundance on JD 208 (p = 0.037), 226 (p = 0.002), and 243 (p = 0.014) compared to JD 107. Additionally, JD 226 had a significantly higher abundance than JD 166 (p = 0.018) but a lower abundance than JD 347 (p = 0.012), reinforcing the trend of declining brown trout abundance toward the later stages of the study period. Brown trout length varied between 4.0 and 28.7 cm.

Signal crayfish abundance also showed significant spatial ($F_{(5,\ 362)}$=22.99, $p < 0.001$) and temporal ($F_{(1,\ 366)}$=79.3, $p < 0.001$) differences (Fig. 4). Tukey's test indicated significantly higher crayfish abundances in sites B2 and B3 compared to site B5 ($p < 0.001$), site B1 compared to site B2 ($p = 0.0038$), B3 ($p = 0.0014$) and B5 ($p = 0.0052$). Additionally, B2 ($p = 0.0032$) and B3 ($p < 0.001$) had significantly higher crayfish abundance than B1. Temporal analysis revealed an increase in abundance after JD 140, peaking around JD 226, followed by a sharp decline (Fig. 4), with a significantly lower crayfish abundance on JD 107 compared to JD 188, 208, 226, 243, and 279 (all $p < 0.05$).

Brown trout as a biological control of signal crayfish

The presence of signal crayfish in the stomach contents of brown trout was low. Among the sampled brown trout, 12.24% showed evidence of signal crayfish in their stomachs, with crayfish representing only 2.13% of the total prey items sampled (Suppl. material 1: table S2 for detailed information). However, signal crayfish accounted for 17.70% of the total biomass of the prey found in the stomach content.

The GLM results (Table 1) indicated that brown trout length ($p < 0.001$), water temperature ($p < 0.001$), and JD day ($p = 0.002$) were significant predictors of signal crayfish predation. Larger trout had a higher probability of consuming crayfish. Water temperature was positively associated with signal crayfish consumption. Conversely, JD showed a negative relationship with signal crayfish predation, indicating a decline in consumption over time. Spatial variation also played a role, as sites B4 ($p = 0.007$) and B5 ($p = 0.001$) showed significantly lower predation rates (Table 1). Signal crayfish abundance, however, was not a significant predictor of predation ($p = 0.394$) (Table 1). Model diagnostics indicated no severe multicollinearity (all VIF < 5), and residual analysis suggested an adequate model fit (Suppl. material 1: fig. S1).

Table 1. Summary of the generalized linear model (GLM) with a binomial distribution and logit link function. The response variable is the presence/absence of signal crayfish in brown trout stomach contents (0 = absent, 1 = present). The predictor variables include trout length (cm), water temperature (°C), total dissolved solids (TDS, mg/L), pH, crayfish abundance (ind. CPUE), sampling site (factor with B1 as reference level), and Julian day. The table presents model estimates, standard errors, z-values, and p-values. Significant effects ($p < 0.05$) are marked with * and highly significant effects ($p < 0.001$) with ***.

Variable	Estimate	Std. Error	z value	p-value
(Intercept)	27.547567	24.844294	1.109	0.26751
Trout Length (cm)	0.308655	0.032958	9.365	< 2e-16 ***
Water Temperature (°C)	0.318505	0.075412	4.224	2.4e-05 ***
TDS	-0.024971	0.018133	-1.377	0.16848
pH	-4.78158	3.434486	-1.392	0.16385
Crayfish Abundance	0.01555	0.018281	0.851	0.39499
Site B2	-0.777836	0.461591	-1.685	0.09197
Site B3	0.075695	0.472005	0.16	0.87259
Site B4	-1.935907	0.724084	-2.674	0.0075 *
Site B5	-4.323871	1.351895	-3.198	0.00138 *
Julian Day	-0.013684	0.004513	-3.032	0.00243 *

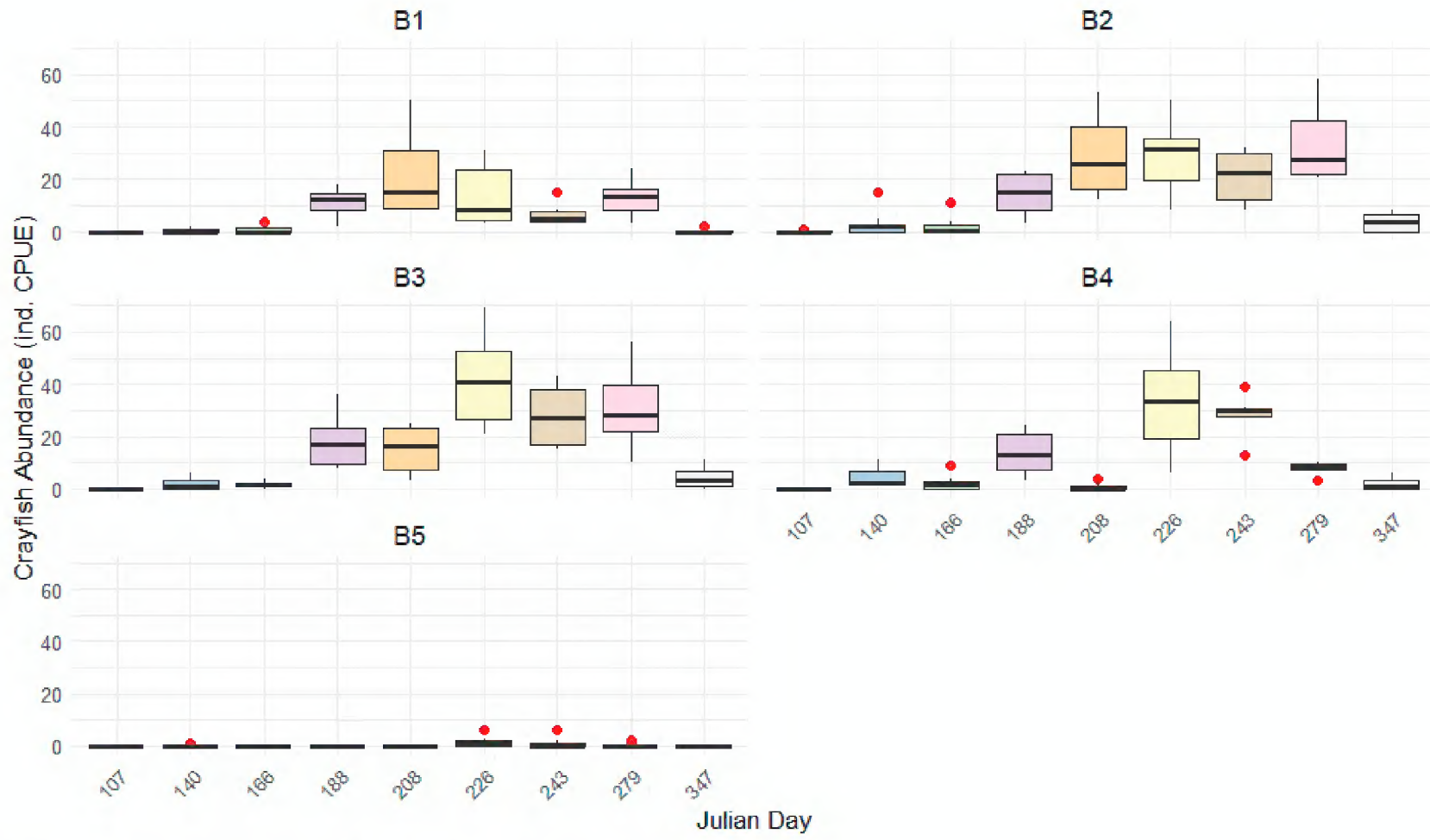

Figure 4. Abundance of signal crayfish over time and sampling sites.

Discussion

The success of non-native species is frequently associated with the lower biotic resistance (lack of parasites, diseases, competitors and predators) of the native communities (Colautti et al. 2004). Despite the presence of signal crayfish in brown trout stomach contents, their occurrence was infrequent, though they contributed significantly to total prey biomass consumed by brown trout. This situation, in addition to the low density of brown trout (if we convert our relative abundance data into density values based on the 1,000 m^2 sampled area at each site and on each occasion) in comparison with other European rivers (Eklöv et al. 1999), even in the Iberian Peninsula (Nicola et al. 2008), suggests that this predator is unlikely to serve as an effective and sole biological control for signal crayfish in the Baceiro River.

Environmental characterization

The results of the environmental characterization showed clear spatial and temporal differences. Downstream sites (B1, B2, and B3) located at a lower altitude had higher conductivity and TDS compared to upstream sites (B4 and B5), with temperature playing a significant role in seasonal variation. Dissolved oxygen and pH remained relatively stable across sites and time of the year. These environmental patterns are particularly relevant because conductivity and TDS, which were higher in downstream sites, may influence habitat preferences of brown trout and signal crayfish. Likewise, temperature variation across sites aligns with observed seasonal trends in both brown trout and crayfish abundance. Anyway, it should be noted that all sites present very low human disturbance, being the Baceiro River an oligotrophic system characterized by clear waters and low nutrient concentrations. Therefore, the spatial changes detected for the analyzed environmental parameters reflect the gradient that typically occurs along the longitudinal profile of watercourses, in the absence of human disturbances, according to the river continuum concept (Vannote et al. 1980).

Brown trout and signal crayfish population dynamics

The peak in brown trout abundance was in the mid-to-late stages of the study period and aligns with seasonal patterns of salmonid populations that are influenced by environmental factors such as temperature and food availability (Lobón-Cerviá 2009; Blanchfield et al. 2023). This observation is in line with the work of Elliott and Elliott (2010), who emphasized the importance of seasonal temperature changes in regulating brown trout population dynamics. However, it should be noted that in these mid-to-late stages of the study period, the river flow is also lower, which may increase the efficiency of electrofishing, contributing to higher abundance values. The spatial variation in brown trout abundance, particularly the lower overall abundance in sites B1, B2, and B3, could be attributed to differences in habitat quality, food availability, the presence of a higher abundance of the non-native signal crayfish, and the higher fishing pressure (Oliveira et al. 2025).

The temporal variations in signal crayfish abundance suggest a strong temperature dependence, with crayfish captures increasing during warmer periods and declining during colder months due to reduced activity. As ectothermic organisms, their metabolism and behavior are temperature-dependent (Rodríguez Valido et al. 2021). Crayfish abundance increased after JD 140, peaking around day 226, before declining, reflecting typical seasonal activity patterns (Hudina et al. 2017). The observed increase in abundance during warmer periods (JD 166–226) likely corresponds to elevated metabolic rates and heightened activity of signal crayfish in response to higher temperatures and so increasing the chances of being captured (Rikardsen et al. 2006; Sousa et al. 2013). The subsequent decline in the autumn and early winter is likely due to decreased activity and burrowing behavior in colder months, providing thermal stability (Payette and McGaw 2003; Hudina et al. 2017). Signal crayfish abundance also varied across sites, suggesting that local factors such as food availability, predation pressure, habitat conditions or interspecific interactions influence distribution (Yarra and Magoulick 2018). Differences may also relate to invasion gradients, where invasion fronts exhibit lower abundances compared to core areas (Hudina et al. 2012; Alves et al. 2025; Carvalho et al. 2025). It should be noted that the Baceiro River site B1 was the first to be colonized by this non-native species and the spread was in the upstream direction, being the current invasion front located at site B5 (first records in this site at the end of the summer 2022; Ronaldo Sousa personal observation).

Brown trout as a biological control of signal crayfish

Only 12% of the brown trout analysed present signal crayfish in their stomach contents. The number of consumed crayfish in comparison to all items identified in the stomach contents was very low (2.13%), but their contribution to the biomass of consumed prey was more considerable (17.70%). The low prevalence and consumption rates of signal crayfish may be attributed to several ecological and behavioral factors. Crayfish possess hard exoskeletons and defensive behaviors, making them more difficult to capture and consume than softer-bodied prey (e.g., aquatic insects and small fish). Furthermore, previous studies have shown that fish predators often exhibit an initial lag in recognizing novel prey (Carroll 2007; Cox 2013), which may explain why brown trout do not yet effectively incorporate crayfish into their diet. Despite being an opportunistic feeder, whose hunting activity

aligns with the crepuscular behavior of crayfish (Sbragaglia and Breithaupt 2022), brown trout may still find it challenging to capture and handle this prey efficiently, resulting in its low occurrence in the diet.

Predation of signal crayfish was higher in warmer months and decreased over the year. Higher water temperatures are typically associated with increased metabolic rates and activity levels for both species (Rikardsen et al. 2006; Lobón-Cerviá 2009; Rodríguez Valido et al. 2021; Carvalho et al. 2022b; Blanchfield et al. 2023). This likely leads to more frequent encounters between predators and preys, explaining the higher predation rates observed in summer.

Signal crayfish consumption was higher in larger brown trout, suggesting that only the largest individuals included crayfish in their diet. This pattern may be explained by morphological and behavioral factors, suggesting that morphological constraints, such as gape size and prey-handling ability, may limit predation in smaller trout, as shown in other fish species such as eels (Aquiloni et al. 2010) and pike *Esox lucius* (Elvira et al. 1996). Larger individuals are more capable of capturing and consuming signal crayfish, particularly juveniles, which are more vulnerable to predation (Momot 1967; Faragher 1983; Dorn et al. 1999). Additionally, a significant correlation was found between signal crayfish abundance and the percentage of empty trout stomachs (data not shown), implying an overall reduction in feeding efficiency or higher interspecific competition when crayfish population abundance was high, this situation being more effective in sites B1, B2 and B3 (Carvalho et al. 2022a).

We also found differences in predation rates along the sampling sites, but these differences mainly rely in a much lower predation in upstream sites B4 and B5. This situation is probably explained by the recent spread of the signal crayfish to these upstream sites, especially site B5 (first detection at the end of the summer of 2022) as could be seen by the very low abundance values presented by this non-native species. The time passed since the invasion (ten years) was probably not sufficient for the brown trout to recognize signal crayfish as a profitable prey. However, information on palatability and handling can spread rapidly through the population, once learnt, mainly when the resource is very abundant (Santamaría et al. 2022). This may intensify the biotic resistance of brown trout as they learn to handle and consume the signal crayfish, potentially leading to a higher predation rate. Anyway, this situation remains speculative in the study area and future studies should evaluate this situation.

Given the limited role of brown trout in controlling the signal crayfish population in the studied area, coupled with their low density, integrating their predation with that of other native predators may provide a more effective and robust approach to biological control. Among the native predators, European eels (*Anguilla anguilla*) and Eurasian otters (*Lutra lutra*) have been identified as key species that prey on invasive signal crayfish in European ecosystems (Blake and Hart 1995; Tablado et al. 2010). Studies have demonstrated that European eels actively prey on juvenile signal crayfish, attacking, killing, and consuming them, with their predation strategy relying more on stealth and ambush than active pursuit (Blake and Hart 1995; Worley 2022). However, eels are not present in our study area for decades, given the presence of downstream dams impeding their migration. Otters have been documented preying on signal crayfish, particularly during warmer months, and although they are opportunistic feeders, their seasonal predation could regulate signal crayfish populations over time (Britton et al. 2017). So, both brown trout and otters could play a role in controlling signal crayfish in the Baceiro River, though further research is needed to assess their

long-term impact. Additionally, the recent introduction of the American mink (*Neogale vison*) in the Baceiro River could contribute to signal crayfish predation but may also alter biotic interactions, potentially causing cascading effects on overall biodiversity, including on brown trout and otters. However, further studies are needed to assess these possible interactions.

Conclusion

While brown trout, particularly larger individuals, can prey on signal crayfish, their overall impact on controlling crayfish abundance in the Baceiro River appears to be limited. This size-dependent predation may have management implications as currently, only trout over 20 cm can be harvested in the Baceiro River, and these larger fish are highly prized by anglers. Therefore, a potential conflict exists between anglers' interests and the role of brown trout as an effective biocontrol agent for signal crayfish. Other native predators, such as the Eurasian otter, also rely on signal crayfish as a primary food source. Therefore, integrating ecological knowledge with conservation measures (e.g., restocking brown trout using individuals produced from genetically selected wild spawners from the study area, modifying fishing regulations) and leveraging native predators such as brown trout and otters could provide a more balanced and sustainable solution for mitigating the impact of signal crayfish in this protected area. Future management measures should also consider integrating multiple control methods (e.g., mechanical removal such as trapping; Moorhouse and Macdonald 2011) to mitigate the impact of signal crayfish while preserving the ecological balance of the Baceiro River ecosystem. Since we are in a protected area that often serves as a privileged observatory for evaluating the impacts of non-native species—due to the absence of other significant human disturbances—the implementation of sustainable management measures and the conservation of native species should be prioritized (and carefully monitored) to fully develop their potential as biological control agents.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualization: RS. Data curation: MM. Formal analysis: MM, RS. Funding acquisition: RS. Investigation: MM, RS, JP, AT, ABN. Methodology: RS, AT. Resources: AT, RS. Writing - original draft: RS, MM. Writing - review and editing: JP, ABN, AT.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Additional information

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